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PHOTONICS AND NANOSTRUCTURES Fundamentals and Applications
Photonics and Nanostructures – Fundamentals and Applications 1 (2003) 63–68
www.elsevier.com/locate/photonics

Fine structural adjustment of lasing wavelengths in photonic crystal waveguide laser arrays

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Received 24 July 2003; received in revised form 24 September 2003; accepted 25 September 2003

Abstract

We propose new and simple designs that allow one to adjust the relative frequency of photonic crystal waveguide lasers included in a laser array. Using numerical simulations, we demonstrate that wavelength shifts smaller than 2 nm can be achieved while remaining compatible with common lithographic precision. Specific details of the implemented methods allow to deal with relative shifts as small as $\approx 2 \times 10^{-4}$.
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PACS: 42.70.Qs; 42.82.Et; 42.55.Px

Keywords: Photonic crystal; Semiconductor laser array; FDTD; Photonic band-diagram; Guided optics

1. Introduction

Photonic crystals (PC) are artificial dielectric structures of particular interest for miniature optical devices in integrated optics. They have recently been used to fabricate small size, edge emitting photonic crystal lasers [1,2]. Modern optical telecommunication systems require compact multi-wavelength light sources among which PC laser arrays are good candidates. As it is known, photonic crystals that are similar to each other and differ only in their lattice constant share the same band diagram scaled by their period ratios in real world units. Since the microfabrication precision is limited [3], this property cannot be directly used to fabricate PC laser arrays with less than 10 nm separation in wavelength. However, common telecommunication standards require a spacing smaller than 1 nm.

Conventional wavelength sources of the standard ITU wavelength grid are semiconductor DFB lasers fabricated on the same semiconductor chip and whose optical outputs are multiplexed. In this paper, we propose an original technique allowing us to finely adjust the wavelength of each PC laser of an array while remaining compatible with common lithographic constraints. We consider a two-dimensional PC edge emitting laser made of a waveguide as the one described in [2]. Using plane-wave based band-diagram calculations and finite difference time domain (FDTD) simulations [9], we show that the relative frequency difference between the lasers can be easily adjusted by a slight perturbation of the photonic crystal. We suppose that all other parameters

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doi:10.1016/j.photonics.2003.09.001

affecting the wavelength are constant from one to another laser of the array (temperature, carrier injection, ...). This approach has some similarities with that of [4] where DFB laser arrays were designed with highly accurate (<0.2 nm) wavelength spacing while the absolute wavelengths of the array were tuned at once thermally.

2. Band diagram engineering

As mentioned above, we are mainly interested in the wavelength shifts of the PC lasers with a slight perturbation of the PC. We consider a photonic crystal waveguide (W1) made by omitting a single row in a two-dimensional triangular lattice PC of air holes: lattice constant $a = 0.35\,\mu$m, air filling factor 28%, effective dielectric index 3.2 (this effective index corresponds to a realistic InP/GaInAsP/InP step index slab waveguide with an embedded quantum well in the waveguide core).

The PC exhibits a band gap between 0.219 and 0.272 (normalized frequency) in TE mode (*H*-polarization). The band diagram (i.e. the eigenfrequencies) of this structure is calculated using a plane wave expansion with the supercell method. The expansion uses 36,864 plane waves and the computation is performed with a publicly available software [5]. The calculations are stopped when the relative accuracy in the eigenvalues is better than 10^{-6}. The overall accuracy is about 0.008% (~0.1 nm at $\lambda = 1550$ nm) for the first guided mode. It was estimated by performing an additional computation where the number of plane waves was multiplied by four and the supercell included four rows more. The band diagram of the studied W1 waveguide is represented in Fig. 1. The *H*-field amplitude of the first guided mode at the *J*-point ($\omega/2\pi c = 0.225$) is also represented. According to [8], the potentially lasing modes are those with the smallest group velocity. However, it appears that the first guided mode at the *J*-point has the best overlap with the guide core. Thus, we can expect that, in an active dielectric medium, this mode will experience the largest gain and the lowest threshold. We verify this point in the next part with an FDTD method.

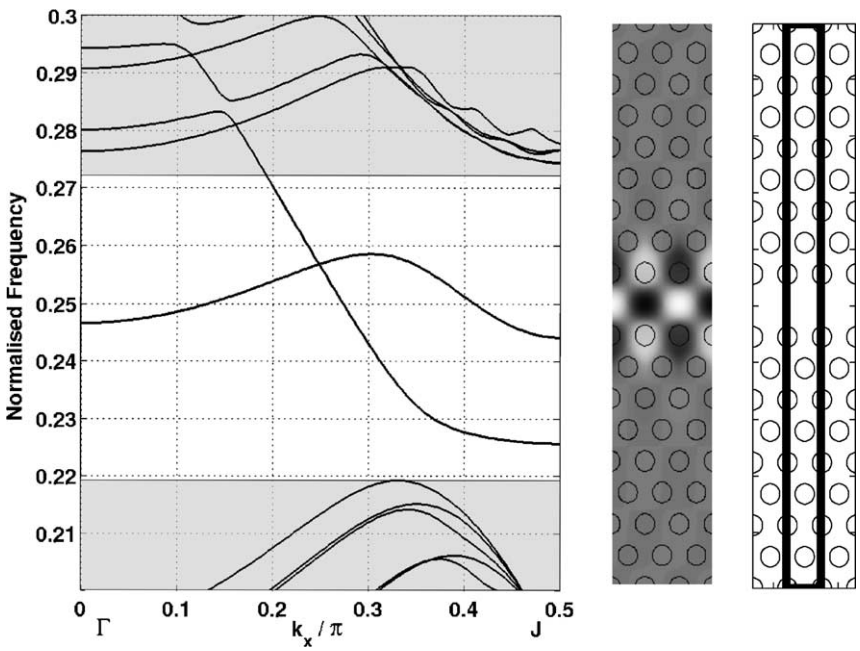

Fig. 1. Band diagram of the W1 waveguide (left) and *H*-field of the first localized mode at the *J*-point (center). The bandgap is between 0.219 and 0.272 (normalized frequency units). A plane wave method is used (~0.008% accuracy) with the supercell as defined in the right figure (thick frame).

Under the lasing conditions (expected at the *J*-point of the band diagram), the first guided mode is strongly localized in the waveguide. Thus, if the parameters of the photonic crystal are perturbed far enough from the defect line, the propagation of the mode and its band diagram will be affected only slightly. In other words, by perturbing the photonic crystal structure far from the center of the waveguide, we hope to slightly change the frequency of the first guided mode without significantly changing other properties of the PC. A simple and current way to change the photonic crystal characteristics is to modify the diameters of some PC holes. Here, we enlarge the holes in two parallel rows at equal distance from the center of the waveguide, namely the first, second, third or fourth closest rows to the waveguide core. As we expect a lasing effect at the *J*-point, we thus compute the wavelength shift at this point when the hole diameter is multiplied by a factor from 1 to 1.48. Results are shown in Fig. 2. The wavelength shift is negative due to the reduction of the effective index with the hole diameters. In contrast, its amplitude increases with the hole diameter. It also increases when the modified row is brought closer to the center of the waveguide. As pointed out, we are only interested in the relative lasing frequencies and not in the absolute frequencies. As in the DFB array context, we suppose that a given laser of the array is tuned to the desired frequency (e.g. thermally). In the last part, we will verify that the variation of the hole diameter due to the fabrication process does not deteriorate these small wavelength shifts.

3. PC laser FDTD simulations

To investigate the lasing frequency of a perturbed W1 waveguide laser, we first simulate a 10.5 μm long and 3 μm wide W1 waveguide with two cleaved facets by a two-dimensional FDTD method (see Fig. 3). This configuration is similar to the experimental one reported in [2]. Perfectly matched layers (PML) are used for boundary conditions. Unlike the assumption of the previous part, the relative dielectric constant $\varepsilon_r = \varepsilon' - i\varepsilon''$ is complex to account for laser gain and losses. In the absence of spontaneous emission, the laser signal is initiated from a fictitious point source localized in the guide core off axis. The point source is assumed to emit a weak transient pulse with a broad spectrum covering the whole forbidden PC gap.

Since we are primarily concerned by the lasing frequency and not the laser output power, the gain in the semiconductor is fixed by the complex part $\varepsilon'' = \sigma/(\omega\varepsilon_0)$ of ε_r, where σ is a constant (negative) conductivity. This value is chosen equal to 0.005 at $\lambda =$

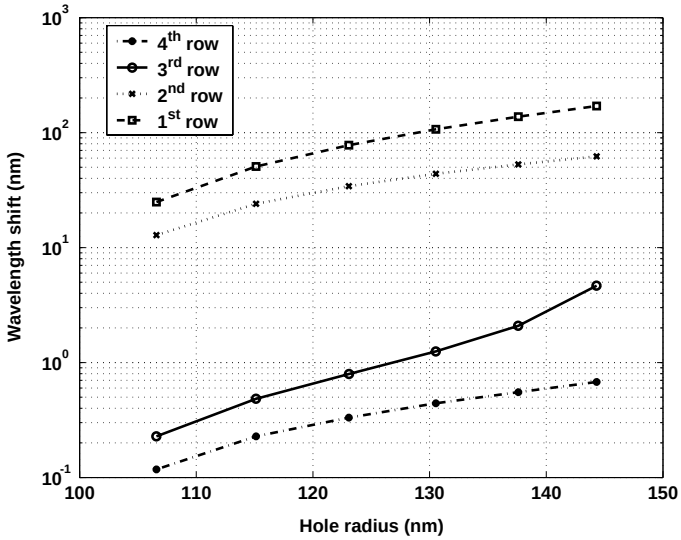

Fig. 2. Absolute value of the wavelength shift in nm vs. the hole radius of the perturbed rows. The unperturbed hole radius is 97 nm and the period is 350 nm (plane wave method).

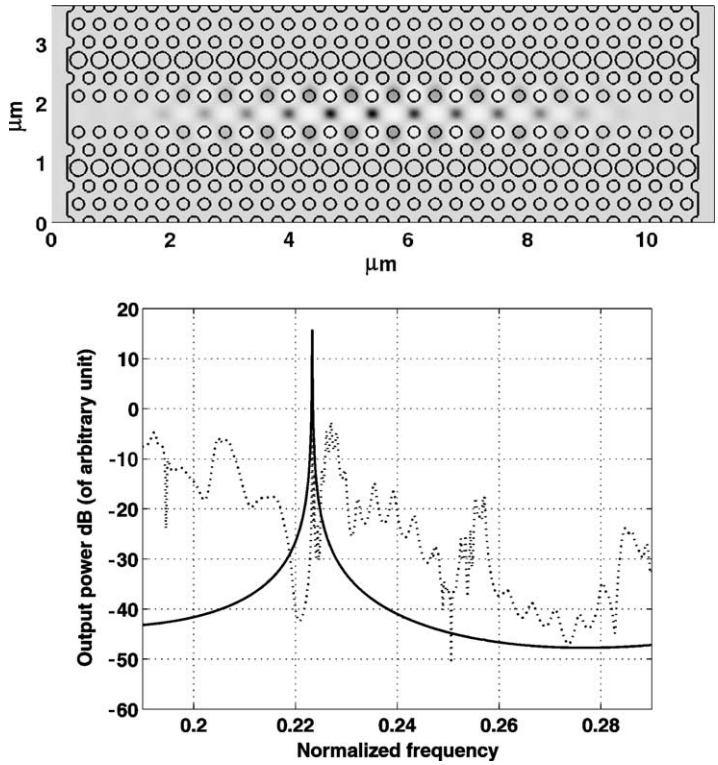

Fig. 3. Top: typical PC waveguide arrangement used in FDTD calculations (the PML surrounding the PC is not represented). In the present case, the third PC row on each side of the waveguide core is modified: the diameter of the 'modified' hole is 1.4 times larger than the nominal diameter. The *H*-field computed by the FDTD method after 10^6 iterations is also represented. Bottom: spectrum computed in transient regime over the 11 first picoseconds (dotted lines) and in laser regime over the 23 following picoseconds (solid lines).

1550 nm and corresponds to a net linear gain $\Gamma g \approx -(2\pi/\lambda_0)(\varepsilon''/n) \approx 60\,\mathrm{cm}^{-1}$, where Γ is the optical confinement factor in the quantum well. This very simple model omits the gain saturation of the medium. As a consequence of these simplifications, the simulated laser never reaches a steady state for the lasing modes: the output power at the lasing frequencies is an increasing function of time. More precise laser models [7] are not necessary for the purpose of this paper. In contrast, it is crucial to avoid excessive time-consuming calculations. Indeed, with the following standard discretization $\mathrm{d}x = 14\,\mathrm{nm}$ (i.e. about one-tenth of the hole diameter) and $\mathrm{d}t = \mathrm{d}x/2c = 2.3 \times 10^{-5}\,\mathrm{ps}$, we have to perform at least 10^6 iterations if we wish to determine by Fourier transform the oscillating wavelength with a precision of 0.35 nm.

Diffractive losses due to the finite depth of the holes in the real photonic crystal are included using a phenomenologic approach [6]: inside the holes, we take ε_r complex and equal to $1 - 0.005i$ at $\lambda = 1550\,\mathrm{nm}$ to simulate diffractive losses.

This estimation is rather conservative since in the literature, the value of ε'' is often taken greater than ours because it is used as a fitting parameter and also includes other loss sources. In our FDTD model, the PC holes are described using a smoothen profile of $\varepsilon_\mathrm{r}(x, y)$ in such a way that the average value of epsilon is conserved over the PC unit cell. This technique is similar to that used in [5] in the case of a plane wave analysis. In these conditions, minute variations of the hole diameters as those introduced further in the text are well incorporated in the calculations even though the d*x* step is larger than the variation amplitude itselves. It was checked that the results remained unchanged when the discretization step d*x* was divided by two.

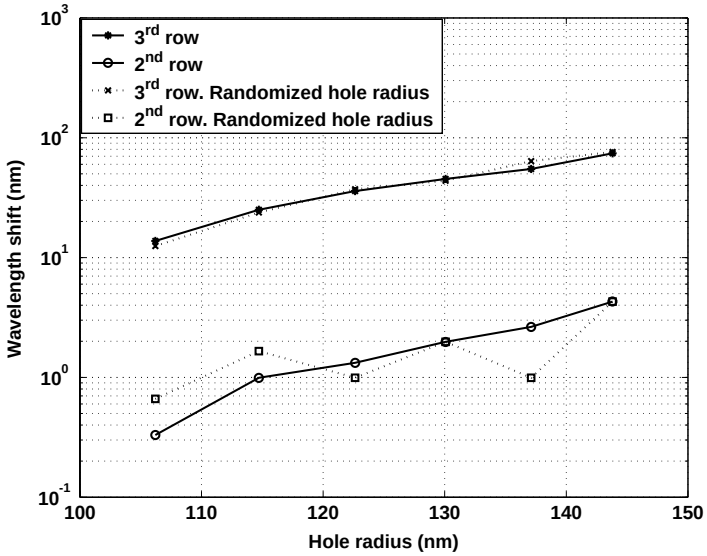

Fig. 4. Absolute wavelength shift vs. the hole radius of the modified rows. In solid line, the different hole radii of the PC structure are fixed. In dotted lines, the different hole radii in the PC structure are randomized around their average value (FDTD calculations).

In nominal conditions (the same diameter for all the PC holes), the lasing first occurs near the 0.225 normalized frequency corresponding to the *J*-point. This verifies the experimental observation reported using a similar structure [2]. For larger gains (larger ε''), it is found that the lasing also occurs at other frequencies where the group velocity is low. The corresponding modes have a larger threshold than the first guided mode at the *J*-point. In the second step of our calculations, we have varied the hole diameter of the second and third rows. In Fig. 4, we observe that the lasing frequency follows the same evolution as the one reported for the band diagram of the passive material (Fig. 2). In fact, the two methods of calculation (plane wave and FDTD) give very close results that confirm the effect and amplitude of the wavelength shifting. The very small discrepancy between the two results is due to the finite length and width of the waveguide in the FDTD method and to the limited precision of the Fourier transform calculations.

Next, in view of an experimental validation, it is important to check that the fine evolution of the lasing wavelength will not be blurred by the imprecision of the fabrication process. A simple simulation has been carried out that consists in randomly varying the hole diameters all over the structure. The results are presented in Fig. 4. For each calculation point, the hole diameter is randomized around an average value using a uniform distribution and a maximum deviation of $\pm 5\%$. In spite of this very pessimistic situation, the results are encouraging (see the dotted lines in Fig. 4): we may expect an accuracy better than 2 nm in the wavelength shift.

4. Conclusion

We have numerically demonstrated the possibility of fabricating a photonic crystal waveguide laser array where each laser wavelength can be finely adjusted with a local perturbation of the photonic crystal. This method is compatible with common technological constraints. Plane wave based eigenmode calculations and FDTD simulations of a finite waveguide structure with gain have given very similar results. It has been shown that the lasing wavelength of a 1.55 μm W1 photonic crystal waveguide laser could be almost continuously varied over 5–15 nm by modifying the hole diameters in PC rows symmetrically located with respect to the waveguide core. The dispersion of the hole diameter due to the fabrication imperfections has been found to have a rather small influence on the

laser wavelength variations. These results are very encouraging for the fabrication of a compact selectable multi-wavelength source required for telecommunication applications. The method we have proposed can also be applied to surface emitting photonic crystal lasers as well as to other photonic crystal structures such as narrow-band filters.

References

[1] T.D. Happ, M. Kamp, A. Forchel, J.L. Gentner, L. Goldstein, Two-dimensional photonic crystal coupled defect laser diode, Appl. Phys. Lett. 82 (1) (2003) 6.

[2] A. Sugitatsu, S. Noda, Room temperature operation of 2D photonic crystal slab defect-waveguide laser with optical pump, Electron. Lett. 39 (2) (2003) 23.

[3] O. Painter, A. Husain, A. Scherer, P.T. Lee, I. Kim, J.D. O'Brien, P.D. Dapkus, Lithographic Tuning of a two-dimensional photonic crystal laser array, IEEE Photon. Technol. Lett. 12 (9) (2000).

[4] D.M. Tennant, T.L. Koch, Fabrication and uniformity issues in $\lambda/4$ shifted DFB laser arrays using e-beam generated contact grating masks, Microelectron. Eng. 32 (1996) 331–350.

[5] Steven G. Johnson, J.J. Joannopoulos, Block-iterative frequency-domain methods for Maxwell's equation in a planewave basis, Opt. Express 8 (3) (2001) 173–190.

[6] H. Benisty, D. Labilloy, C. Weisbuch, C.J.M. Smith, T.F. Krauss, A. Béraud, D. Cassagne, C. Jouanin, Radiation losses of waveguide-based two dimensional photonic crystal: positive role of the substrate, Appl. Phys. Lett. 76 (2000) 532–534.

[7] S.C. Hagness, R.M. Joseph, A. Taflove, Subpicosecond electrodynamics of distributed bragg reflector microlaser: results from finite difference time domain simulation, Radio Sci. 31 (4) (1996) 931–941.

[8] K. Sakoda, Optical Properties of Photonic Crystals, Springer, Berlin, 2001.

[9] A. Taflove, Computationnal Electrodynamics: The Finite-difference Time-domain Method, Artech House 1995.